Study of luminosity and spin-up relation in X-ray binary pulsars with long-term monitoring by MAXI/GSC and Fermi/GBM

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We study the relation between luminosity and spin-period change in X-ray binary pulsars using long-term light curve obtained by the MAXI/GSC all-sky survey and pulse period data from the Fermi/GBM pulsar project. X-ray binaries, consisting of a highly magnetized neutron star and a stellar companion, originate X-ray emission according to the energy of the accretion matter onto the neutron star. The accretion matter also transfers the angular momentum at the Alfven radius, and then spin up the neutron star. Therefore, the X-ray luminosity and the spin-up rate are supposed to be well correlated. We analyzed the luminosity and period-change relation using the data taken by continuous monitoring of MAXI/GSC and Fermi/GBM for Be/X-ray binaries, GX 304−1, A 0535+26, GRO J1008−57, KS 1947+300, and 2S 1417−624, which occurred large outbursts in the last four years. We discuss the results comparing the obtained observed relation with that of the theoretical model by Ghosh & Lamb (1979).

1. Introduction

X-ray binary pulsars (XBPs) are systems consisting of magnetized neutron stars and mass-donating stellar companions. Since the neutron stars are strongly magnetized, the matter flows from the companion are dominated by the magnetic pressure inside the Alfven radius, and then funneled onto the magnetic poles along the magnetic field lines. The accretion matter also transfers its angular momentum at the Alfven radius. Therefore, the pulsar spin-up rate and the mass accretion rate, i.e. the X-ray luminosity, are thought to be closely correlated (e.g. Ghosh & Lamb 1979, hereafter GL79 [1]). The issue is relevant to the fundamental parameters of the neutron stars such as mass, radius, and magnetic field, as well as the XBP evolution scenarios.

Be XBPs, which include Be stars extending circumstellar disk around the equator, are one of the major XBP subgroups [2]. They often exhibit large outbursts lasting for about a few weeks to a few months mostly at around the orbital phase of the neutron-star periastron passage. During these outbursts, simultaneous spin-up episodes are often observed (e.g. [3]). This is naturally explained by an increase in the accretion rate induced by the interaction with Be-star disk, and the associated transfer of the angular momentum to the neutron star via disc-magnetosphare coupling. These events give us an opportunity to study the relation between the luminosity and the spin-up rate quantitatively.

In this paper, we present the study on the relation using the long-term light curve obtained by the MAXI/GSC all-sky survey and the period change obtained from the archived results of Fermi/GBM pulsar project. These data, taken by the continuous monitor for over four years, enable us to investigate their time variations over the entire outburst activities in Be XBPs. We describe the observation in § 2, the analysis procedure in § 3, and then discuss about the obtained results in § 4.

2. Observation Data

Since the MAXI (Monitor of All-sky X-ray Image; [4]) experiment onboard the International Space Station started in 2009 August, the GSC (Gas Slit Camera; [5]), one of the two MAXI detectors, has been scanning almost the whole sky every 92-minute orbital cycle in the 2–30 keV band. To obtain the long-term luminosity variation of Be XBPs covering the outbursts as well as the intermission/quiescence, we use archived GSC light-curve data in 2–20 keV band, which are processed with a standard procedure [6] by the MAXI team and archived at MAXI web site[7].

The GBM (Gamma-ray Burst Monitor; [8]) onboard the Fermi Gamma-Ray Space Telescope, is an all-sky instrument sensitive to X-rays and gamma-rays with energies between 8 keV and 40 MeV. The Fermi GBM pulsar project [9, 10] provides results of timing analysis of a number of positively detected X-ray pulsars, including their pulsation periods and pulsed fluxes via the web site [11] since the in-orbit operation started in 2008 July. We utilized the archived pulse period data of Be XBPs.

We selected five Be XBPs, GX 304−1, A 0535+26, GRO J1008−57, KS 1947+300 and 2S 1417−624 from targets listed in the MAXI/GSC and the Fermi/GBM archive for this study, because they exhibited large outburst activities in the last four years and their surface magnetic fields are well determined by the cyclo-

ton resonance feature in the X-ray spectrum (execpt for 2S 1417−624). Table I summarized characteristic parameters of these Be XBPs and figure 1 shows the time variation of the bolometric luminosity calculated from MAXI/GSC 2–20 keV light curve data and that of the pulse period obtained from the Fermi/GBM pulsar data during outbursts for each source.

3. Analysis

Observed pulse-period variations of XBPs include two distinct effects, the intrinsic pulsar spin-period change and the orbital Doppler effect. In Be XBPs, both of them are supposed to correlate with the orbital phase. Therefore, it is not straightforward to resolve each component from the observed data. Although the pulse period data of XBPs in the Fermi/GBM archive are corrected for the orbital Doppler effect if their orbital elements are determined, the orbital elements have not been known in all of the Be XBPs with our interests. Hence, we construct a semi-empirical model implementing both these effects and then fit it to the data, in an attempt to simultaneously determine the intrinsic pulse period change and the orbital elements.

3.1. Modeling of period change in XBPs

We here employ the simple theoretical model of the pulsar spin-up by the mass accretion via disk, proposed by GL79 [1]. The model has been examined with X-ray data, and its validity and limits are well studied (e.g. [3, 13]). In this model, the pulsar spin-up rate $-\dot{P}_{\rm spin}$ (s yr^{-1}) is given by

$$-\dot{P}_{\rm spin} = 5.0\times10^{-5}\mu_{30}^{2/7}n(\omega_{\rm s})S_1(M)P_{\rm spin}^2L_{37}^{6/7} \quad (1)$$

$$S_1(M) = R_6^{6/7}(M/M_\odot)^{-3/7}I_{45}^{-1}$$

where μ_{30}, $R_{\rm NS6}$, $M_{\rm NS\odot}$, I_{45}, $P_{\rm spin}$, L_{37} are the magnetic dipole moment of the neutron star in units of 10^{30} G cm^3, radius in 10^6 cm, mass in $M_\odot$, moment of inertia in 10^{45} g cm^2, spin perid in s, luminosity in 10^{37} erg s^{-1}, $n(\omega_{\rm s})$ is a dimensionless torque that depends on the fastness parameter $\omega_{\rm s}$ and approximately constant at ~ 1.4 in slow rotating pulsars satisfying $(P_{\rm spin}L_{37}^{3/7}) \gg 1$.

The equation 1 implies that the spin-up rate $-\dot{P}_{\rm spin}$ follows the luminosity L as $-\dot{P}_{\rm spin} \propto L^{6/7}$. The power-law index γ in a model of $-\dot{P}_{\rm spin} \propto L^{\gamma}$ obtained from the fit to the observed data sometimes disagreed with the theoretical value of 6/7 and favor the rather higher value of ~ 1.2 [3, 13]. Besides this, the comparison of absolute spin-up rate with equation 1 has been hampered by a large uncertainty in the bolometric luminosity correction, which is in turn due to beaming effects (e.g. [3, 12]). We hence employ the spin-up model expressed by

$$-\dot{P}_{\rm spin} = \alpha L_{37}^{\gamma} \quad (2)$$

in which the power-law index $\gamma = 6/7$ and a correlation factor, $\alpha = 1.7\times10^{-7}\mu_{30}^{2/7}P_{\rm spin}^2$ s d^{-1} $(=\alpha_0)$ reduced from the equation 1 and typical neutron-star parameters of $R_6 = 1$, $M = 1.4M_\odot$, $I_{45} = 1$, are treated as free parameters.

XBPs are also known to spin down during the quiescence due to the propeller effects. The rate is much smaller than the spin-up during the outburst bright phases, but may not be negligible. We accounted its effect with a constant spin-down parameter, β, added to $\dot{P}_{\rm spin}$ as an offset.

By combining the spin-up and spin-down models above, the intrinsic pulsar-spin period $P_{\rm spin}(t)$ is expressed by

$$\begin{aligned} P_{\rm spin}(t) &= P_0 + \int_{\tau_0}^{t}\dot{P}_{\rm spin}(\tau)d\tau \\ &= P_0 + \int_{\tau_0}^{t}\left\{-\alpha L_{37}^{\gamma}(\tau)+\beta\right\}d\tau \end{aligned} \quad (3)$$

where we set the time basis τ_0 at the first periastron passage in the period under analysis and define the pulsation period at the time τ_0 as $P_0 = P_{\rm spin}(\tau_0)$. The model equation 3 includes four free parameters, P_0, α, β, γ and requires the luminosity data $L_{37}(t)$ as a function of time. We calculated the luminosity from data of the MAXI/GSC 2–20 keV light curve in 1-d time bin assuming the source distance, the typical energy spectrum of a cutoff power law from the past results, and the source emission to be isotopic.

The period modulation due to the binary orbital motion is calculated by using the binary elements, which consists of orbital period $P_{\rm B}$, eccentricity e, projected semi-major axis $a_{\rm x}\sin i$, epoch τ_0 and argument ω_0 of the periastron. The pulsar orbital velocity $v_{\rm l}(t)$ along the line of sight is

$$v_{\rm l}(t) = \frac{2\pi a_{\rm x}\sin i}{P_{\rm B}\sqrt{1-e^2}}\left\{\cos\left(\nu(t)+\omega_0\right)+e\cos\omega_0\right\} \quad (4)$$

where $\nu(t)$ is a parameter called 'true anomaly' describing the motion on the elliptical orbit and calculated from the Kepler's equation. The observed pulse period, $P_{\rm obs}(t)$, is then expressed by

$$P_{\rm obs}(t) \simeq P_{\rm spin}(t)\left(1+\frac{v_{\rm l}(t)}{c}\right). \quad (5)$$

3.2. Period-change model fit

We applied the spin-period-change model, $P_{\rm spin}(t)$ in equation 3, to the Fermi/GBM archived period data

Table I Characteristic parameters of selected Be X-ray binary pulsars and the best-fit parameters (α, β) used in the period change model.

Target name	$P_{\rm pulse}$ (s)	$P_{\rm orbit}$ (d)	$a_{\rm X} \sin i$ (lt-s)	e	B (10^{12} G)	D (kpc)	α/α_0	β (10^{-9} s s^{-1})	Ref.
GX 304−1	275	132.19	500	0.5	4.7	2.0	0.28	2.0	[15, 16]
A 0535+26	103	111.10	267	0.47	4.3	2.4	1.3	3.6	[17, 18]
GRO J1008−57	93	249.48	530	0.68	6.6	5.8	0.49	2.5	[19, 20]
KS 1947+300	18	40.42	137	0.034	1.1	10	3.2	0.69	[21, 22]
2S 1417−624	17	42.18	188	0.44	–*	11	(6.8)*	0.0:fix	[23, 24]

*: The surface magnetic field B has not been measured. It is assumed to be 2×10^{12} G.

for A 0535+26, KS 1947+300, and 2S 1417−624, in which the binary orbital effects were corrected with the known orbital elements. About GRO J1008−57, the orbital effects are not corrected in the archived data, but the orbital elements have been estimated by [19]. We thus fit the data to the period model, $P_{\rm obs}(t)$ in equation 5, which includes the orbital effect, employing the orbital elements given in [19]. About GX 304−1, its orbital elements have not been measured. We fit the period data with the model $P_{\rm obs}(t)$ in which the orbital elements are floated.

As results of many model-fit attempts, we found that the model is able to reproduce the data approximately with $\gamma \sim 1$ in all of the five targets. We thus fix the parameter γ at 6/7, predicted by GL79 [1], in order to concentrate on the correlation factor α, hereafter. In figure 1 bottom panels, the obtained best-fit models with $\gamma = 6/7$ are superposed on the period data. The best-fit parameters are shown in table I, where the values of α are given by the ratio to that ($= \alpha_0$) predicted by GL79 [1].

4. Discussion

We fitted pulse period variation of five Be XBPs observed with Fermi/GBM to the model implementing the spin-up due to the mass accretion via disk, expressed by $\dot{P}_{\rm spin} = \alpha L^{6/7}$ based on GL79 [1] and the luminosity estimated from the MAXI/GSC light curve. The results show that the model successfully reproduce the data in all of the five samples. The obtained best-fit parameters imply that the correlation factor α from the luminosity $L^{6/7}$ to the spin-up rate $\dot{P}$ largely agree with α_0 predicted by GL79 [1]. The dispersion of the ratio, $\alpha/\alpha_0 \sim 0.3$ to 3, is naturally expected from the uncertainty in the bolometric luminosity correction due to the beaming effect.

However, the values of α/α_0 seems to have some tendency against the pulse period, the orbital period, and the eccentricity, which are suggested to have a relation with Be-XBP subgroups [14]. This will become clearer with increasing data in the near future.

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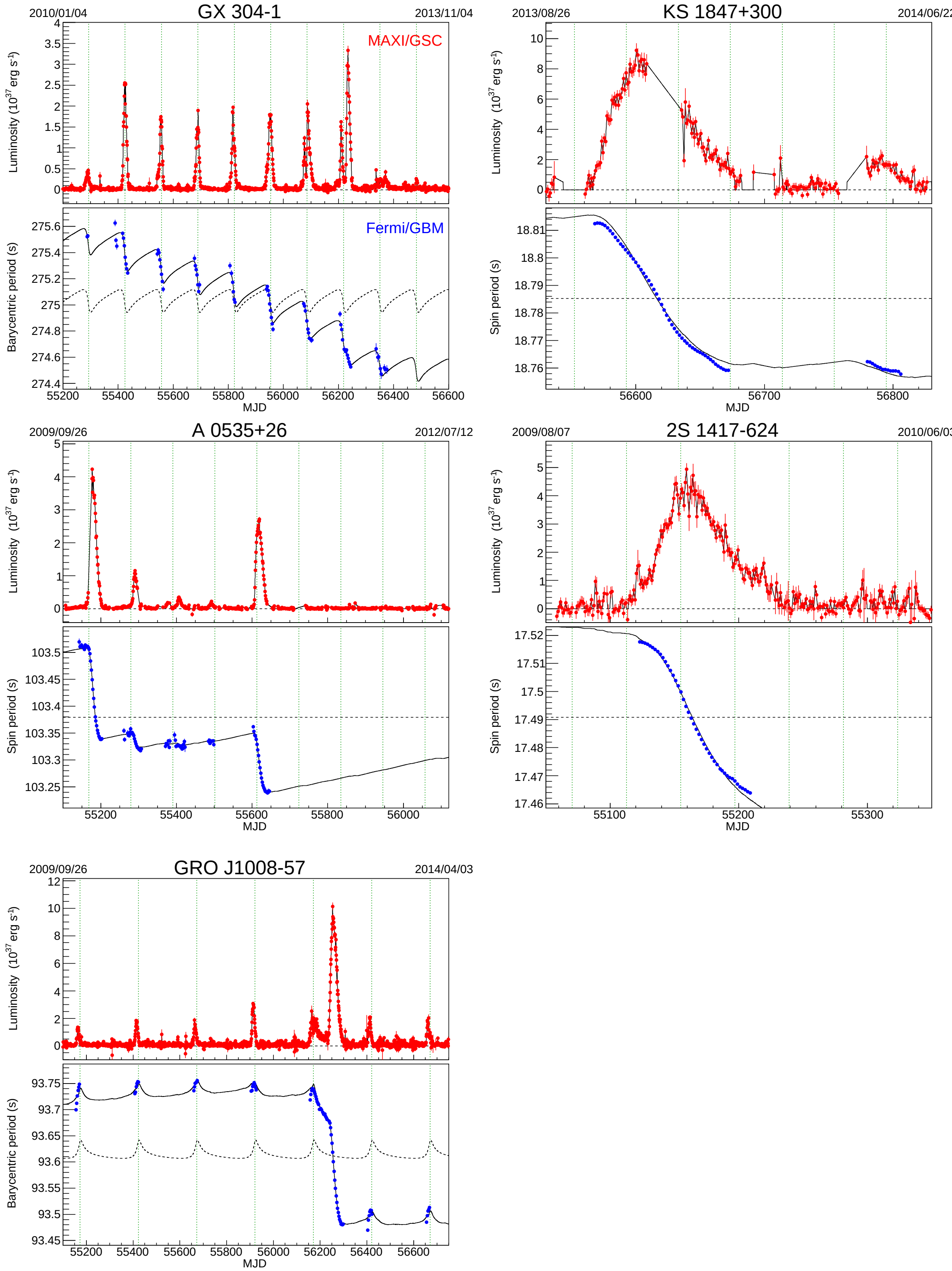

Figure 1: For each target of GX 304−1, A 0535+26, GRO J1008−57, KS 1947+300, and 2S 1417−624, time variation of luminosity estimated from MAXI/GSC 2–20 keV light curve data in 1-d time bin (top) and and that of pulse period during the outbursts obtained from Fermi/GBM pulsar data (bottom) are plotted. In the top panels, solid lines represent the luminosity data $L_{37}(t)$ used for the period-change model fit. In the bottom panel, solid and dash lines represent the best-fit period model and the inclusive orbital Doppler effects which have been corrected in A 0535+26, KS 1947+300, and 2S 1417−624.